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The influence of rock fragments on field capacity water content in stony soils from hard sandstone alluvium

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ABSTRACT

Worldwide, rock fragments (RFs) are generally considered inert with respect to bulk soil hydraulic properties, such that all soil water retention properties predicted by national pedotransfer functions (such as S-map) are based on the volumetric fraction of the fine earth (<2 mm fraction) only. Research findings contradict those assumptions, but studies commonly focus on porous RFs, and rely on repacked cores and lab studies, leaving uncertainty as to how low porosity RFs characteristic of common strongly indurated lithologies affect soil in the field. We address this question by examining soil water storage in 52 pits excavated into stony soils on the Canterbury Plains, New Zealand, which are formed in sediment derived from a Mesozoic hard sandstone. The soils at each site were watered to saturation, and then after two days of drainage (a proxy for field capacity), a 30 × 30 cm pit was excavated in 10 cm increments to a depth of 60 cm. From each increment, soil samples were collected and analysed to determine the volumetric size distribution of RFs, the water content of the fine earth and the water content of the RFs themselves. Our results indicated that RFs could influence the fine earth bulk density, porosity, and soil chemistry. RFs could also retain water: 2–20 mm RFs (0.07 m^3 m^{-3}) retained twice as much water as >20 mm RFs (0.03 m^3 m^{-3}). The water retention of the hard sandstone was low compared to other lithologies, but the volumetric abundance of RFs in the stony soils we sampled meant that they accounted for ~10% of the water retained to a depth of 60 cm at field capacity. Our results demonstrate that ~13 mm of water retained by RFs at field capacity is not currently considered in water budgets and nutrient leaching predictions, which may be relevant to best practice land management.

1. Introduction

Worldwide, there are concerns about rising nutrient concentrations in surface and groundwater systems. A leading source of leached nutrients is agricultural land, which has expanded in area and is being used more intensively on account of increasing global food demand. To mitigate nutrient leaching, more effective land management practices and nutrient discharge regulations are necessary, making knowledge of soil water and nutrient retention properties indispensable. To provide the data needed, a number of countries are developing national datasets of these key soil water properties (Hallett et al., 2017; McNeill et al., 2018), while other organisations are developing datasets at the international and global scale (Baruck et al., 2016; Batjes, 2009; Dai et al., 2019; Shangguan et al., 2014). These datasets commonly rely on pedotransfer functions to estimate properties such as the water content at field capacity (FC). But, the accuracy of any model depends on the representativeness of the data used for model development and validation. Currently, soils containing rock fragments (RFs) are frequently understudied, with most soil information systems and models relying on the assumption that RFs retain no water (Pineda et al., 2018; Román Dobarco et al., 2019). However, international studies have shown that depending on the shape, size, degree of weathering and lithology, RFs are capable of significantly influencing soil hydro-physical properties (Hlavacikova et al., 2015). For instance, Korboulewsky et al. (2020)

Abbreviations: FC, field capacity; RF, rock fragment; SSA, specific surface area; VWC, volumetric water content.

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found that ignoring the water retained in limestone pebbles could equate to a 30% underestimation of soil available water content, while pumice RFs at saturation have been measured with VWC of 0.55 (Parajuli et al., 2017). Even RFs with higher densities, such as fine-grained sandstone, can have VWCs between 0.03 and 0.4 when at saturation depending on RF size and weathering (Parajuli et al., 2017; Schoeman et al., 1997). This could have significant impacts to the management of stony soils (soils with > 35% RFs by volume within 45 cm of the soil surface to a depth > 100 cm, Webb and Lilburne, 2011), which are being increasingly used for intensive irrigated agriculture (Carrick et al., 2013b). However, the research that has been conducted on stony soil hydraulic properties, especially regarding water retention, utilise repacked soils or lab-based measurements. The few field-based studies in the literature demonstrate that RFs can significantly affect the water retention and drainage properties of stony soils but do not detail how RFs can affect the water holding properties of the fine earth fraction, or quantify the actual volumetric/gravimetric WC of the RFs themselves at FC (Al-Yahyai et al., 2006; Scheinost et al., 1997). Considering repacked soil is unlikely to represent the pore network and hence the proper hydraulic dynamics of undisturbed stony soil (da Silva et al., 2016), a potentially significant research gap remains internationally in how RFs influence the water storage of stony soils *in situ.*

The aim of our paper is to determine the effect of RFs and irrigation on water storage in undisturbed stony soils formed from fine-grained hard sandstone. To do this, 24 stony soil sites across Canterbury, New Zealand, were sampled to cover a range of RF abundance, RF size, soil carbon content and texture, to encompass as much of the variability that occurs in these soils as possible. The purpose is to provide a better understanding of the water retention at FC in stony soils so that this parameter remains meaningful for soil and environmental management in the context of these soils.

2. Materials and methods

2.1. Site information and fieldwork

Sampling sites were located on the Canterbury Plains, on the South Island of New Zealand (Fig. 1). The sampling locations were distributed over two geomorphic surfaces of Pleistocene and Holocene age. Landforms on the Plains are dominated by coalescing Pleistocene glacial outwash fans derived from indurated muddy fine sandstone (greywacke) of the Rakaia terrane sourced from the Southern Alps (Forsyth et al., 2008). The fans are characterised by a relict braided channel pattern except where this is buried by loess or at the fan toes where other depositional environments (floodplain, coastal, swamp) exist. Most of the soils on the Canterbury Plains are shallow stony soils (Carrick et al., 2013a). Significant soil orders (Hewitt, 2010) on the late Pleistocene surfaces include Brown Soils (Dystrudepts and Dystrustepts in Soil Taxonomy), and Recent Soils (Fluvents and Ustepts) on the Holocene age surfaces (Hewitt, 2010; Manaaki Whenua - Landcare Research, 2019).

Fifty-two sampling locations were selected, spanning 24 sites on land under pasture for a minimum of three years and which were predominantly grazed by dairy cattle. At each site, a minimum of two locations were selected for pit sampling, with one site under a sprinkler irrigator for a minimum of 2 years, and the other in the same paddock but in soil that had never been irrigated (e.g. in the corner of the paddock outside the arc of a centre pivot irrigator). The time-consuming nature of the sampling and the sample size made it necessary for fieldwork to be extended over the Austral winter to early spring months of 2017 and

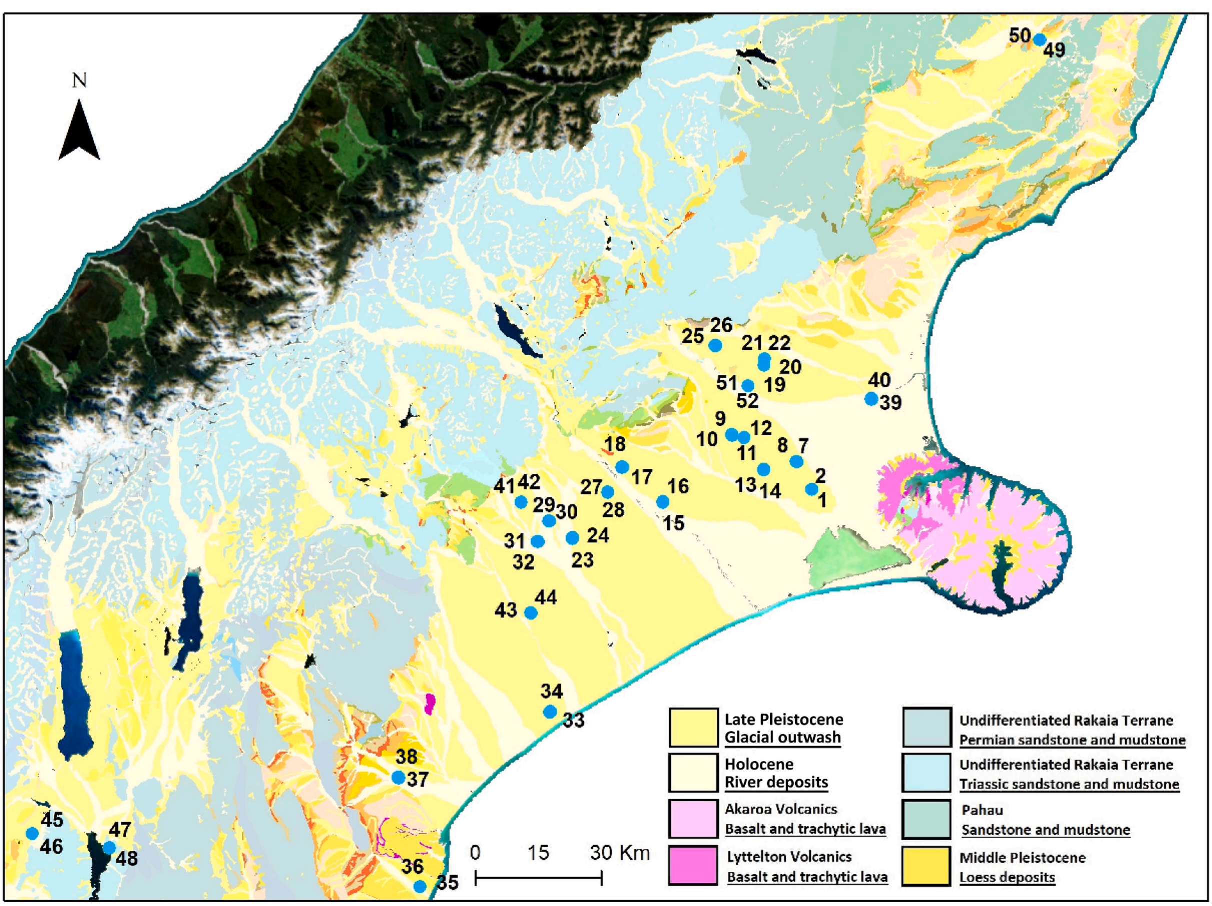

Fig. 1. Geology of the Canterbury Plains and the location of pits. Contains data sourced from the LINZ Data Service licensed for reuse under CC BY 4.0.

2018 (May to September). Sampling occurred during this period because rainfall is greater, with low evapotranspiration, resulting in consistently high antecedent soil moisture which ensures there are no 'dry spots' or hydrophobicity in the soil. The season in which sampling occurred was included in the regression analysis to account for any temporal influences (refer to Section 2.3). For each sampling location, the soil was first wet-up through ponded infiltration. Infiltration was conducted by first clearing the sampling location of above-ground vegetation. Using a 50 cm diameter infiltration ring, two-litre volumes of water (equivalent to 1 cm application depth) were applied consecutively until infiltration times became constant (after ~ 100 mm of water). For soils sampled in spring, the potentially greater evapotranspiration may see greater drying of the soil matrix, with a risk of not being fully rewet if water is applied by ponded water alone. To minimise this risk, an irrigation system was used to add a further circa 110 mm of water to ensure saturation was achieved. The irrigation system covered an area of 60 × 50 cm, greater than the area to be sampled to ensure no boundary effect. The system comprised six lines of Aqua-TraXX 1.14 L/h drip tape, spaced at 10 cm intervals and emitters every 10 cm. Water was gravity supplied from a tank using a garden water timer to apply irrigation for 15 min every hour at a rate of 9 mm/hr over a period of 12 h. Following the wetting of soil profiles (whether by ponded water alone or by ponded and irrigated water), the soil was then covered to prevent evapotranspiration losses or additional rainfall input for 48 h as a proxy for FC. We chose a time-based criterion for field capacity on the strength of Twarakavi et al's. (2009) work, which showed a time basis to be more robust than matric potential based approximations of FC, and a duration of two days because of the rapid drainage of coarse stony soils (Carrick et al., 2017; Graham et al., 2018).

After the 48 h drainage period, the soil was excavated in 10 cm increments to a depth of 60 cm, within a 30 × 30 cm metal frame centred at the middle of the wetted area of the infiltration ring (Fig. 2). At each increment, the matric potential was measured by inserting a UMS T5 pressure transducer tensiometer horizontally into the pit wall, with readings taken with an Infield 7C handheld read-out device (UMS, 2009).

The volume of the individual increments and the pit as a whole were estimated by the pit and bead method (Fig. 2), which is the standard method for measuring volume in stony soils in New Zealand (Hedley et al., 2012). This method can accommodate inconsistencies in pit dimensions caused by the roughness RFs create in the pit walls, either by protruding into the pit or leaving holes in the side of the pit when removed. Before any excavation had occurred, a plastic bag was placed inside the frame and filled with plastic beads, which were levelled off flush with the lip of the frame. Beads were then weighed and recorded as the 'dead weight', which represented the volume between the soil surface and the top of the frame. After each increment was excavated, the pit was lined with a plastic bag, backfilled with plastic beads and made flush with the lip of the metal frame, making sure to fill in cavities between protruding RFs and the edges of the pit. The beads were then weighed and converted to a volume using the bulk density of the beads (0.562 Mg/m^3). As this method calculates the volume of the whole pit, the volume of any one depth increment (V_T) required the volume of the previously dug, shallower increments to be subtracted. For instance, the volume of the 40–50 cm increment would equal the pit volume to 50 cm minus the pit volume to 40 cm, while the 0–10 cm increment volume would equal the pit volume to 10 cm minus the dead volume.

Excavated material for each depth increment was passed through a 20 mm sieve in the field. All the largest (>20 mm) RFs were collected and weighed (M_{RF}) to avoid any biases introduced by sub-sampling. The <20 mm fraction, called the coarse fines, was weighed (M_{CF}) before being thoroughly mixed, spread out in a large sampling tray and quartered. One quarter was collected and weighed (M_b) for the purpose of estimating the whole soil bulk density, the fine earth bulk density and the 2 – 20 mm RF size distribution and the WC of the 2–20 mm RF fraction. One scoopful (with a trowel) was collected and weighed (M_θ) for estimating the WC of the fine earth, as well as the specific surface area (SSA) of the fine earth (for methods see below). A second quarter of the coarse fines was sieved at 10 mm; the <10 mm material was used for soil carbon, particle size analysis and WC of the fine earth at −1500 kPa. Soils were then described according to the terminology of Milne et al. (1995) and classified to the subgroup level of the New Zealand Soil Classification according to Hewitt (2010).

2.2. Laboratory analysis

The progression of measurements throughout field and lab work is shown in Fig. 3. The <20 mm bulk density subsample and the >20 mm sample were weighed at field moisture (M_b and M_{RF} respectively) and after being oven-dried at 105 °C ($M_{b,od}$ and $M_{RF,od}$, respectively). The samples were then wet sieved into rock size classes defined by Milne et al. (1995) (2–6 mm, 6–20 mm, 20–60 mm and > 60 mm). RFs were then thoroughly cleaned by hand or by agitating them with a gold panning-like action. Clean RFs were oven-dried at 105 °C and weighed according to their size classes ($M_{b,[2.6],\mathrm{cod}}$, $M_{b,[6.20],\mathrm{cod}}$, $M_{RF,[20.60],\mathrm{cod}}$ and $M_{RF,[\rangle 60],\mathrm{cod}}$). The volumes of the RFs were then estimated by assuming a rock density of 2.65 Mg/m^3, which is a density for this rock type that is commonly used in studies (Lee, 2019). To determine the accuracy of this rock density value, RF volume estimations were compared to results measured using the volume displacement method. Trial measurements had a variation of <2% between estimated and measured RF volumes, which was deemed negligible. The volumes of two size fractions of RFs were calculated:

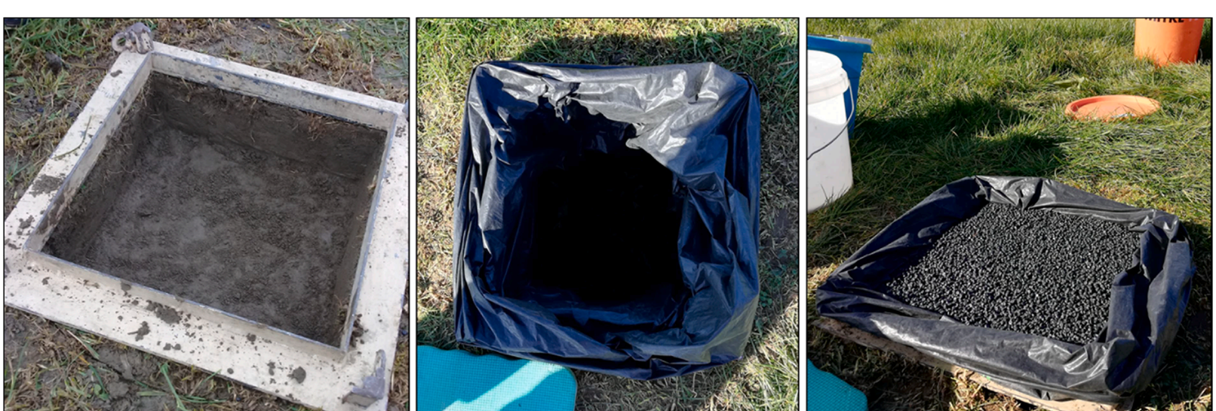

Fig. 2. Pit and bead method (from left to right). Metal frame fitted flush to soil surface, soil material is excavated in depth increments, and volume of the excavated hole is estimated with plastic beads.

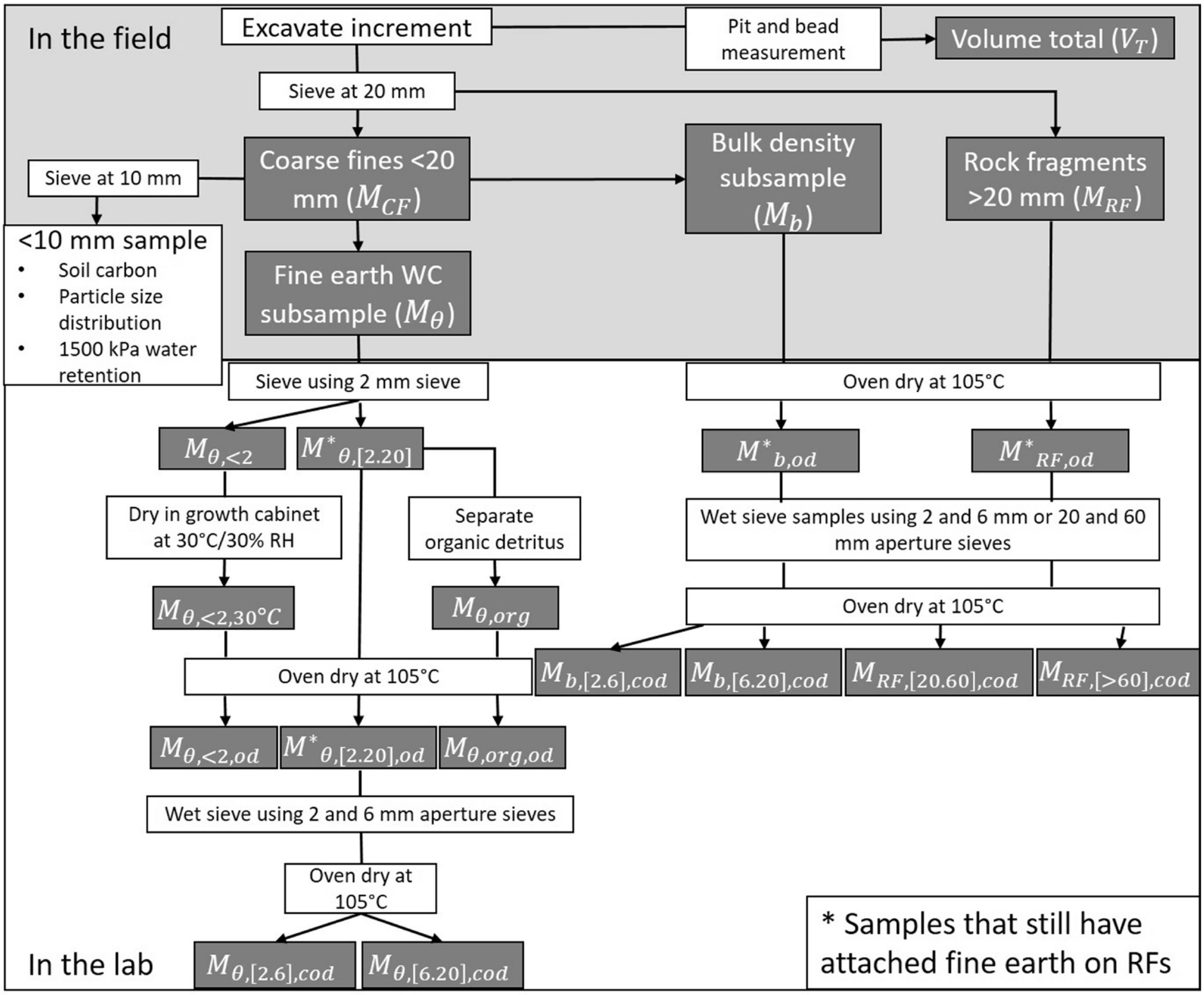

Fig. 3. Flow chart of measurements taken throughout field- and labwork.

$$V_{T[>20]} = \frac{M_{RF,[20.60],cod} + M_{RF,[>60],cod}}{2.65} \tag{1}$$

$$V_{T[2.20]} = \frac{R\left(M_{b,[2.6],cod} + M_{b,[6.20],cod}\right)}{2.65} \tag{2}$$

A scaling ratio (R) was also calculated as a means of extrapolating measures from the bulk density subsample (such as $M_{b[2-6]}$ or M_{b-d}) to the whole depth increment.

$$R = \frac{M_{CF}}{M_b} \tag{3}$$

The volume of the fine earth ($V_{T<2}$) was back-calculated using the volume of the RFs and the total volume of the increment (V_T) measured using the pit and bead method.

$$V_{T<2} = V_T - V_{T[>20]} - V_{T[2.20]} \tag{4}$$

The whole soil bulk density (ρ_b) was estimated by,

$$\rho_b = \frac{M_{b,od}.R + M_{RF,od}}{V_T} \tag{5}$$

while the fine bulk density ($\rho_{<2}$) was estimated by

$$\rho_{<2} = \frac{R\left(M_{b,od} - M_{b,[2.6],cod} - M_{b,[6.20],cod}\right) + \left(M_{RF,od} - M_{RF,[20.60],cod} - M_{RF,[>60],cod}\right)}{V_{T<2}} \tag{6}$$

The second term in the numerator of Eq. (6) ensures any fine earth attached to coarse RFs is included. The fine earth WC subsample was sieved at field moisture through a 2 mm sieve, separating the sample into the <2 mm fine earth and the >2 mm material, which included the >2 mm RFs, attached fine earth (the fine earth adhered to RFs) and organic detritus (roots and other plant material). The <2 mm fine earth was weighed at field moisture ($M_{\theta,<2}$), again after being dried in a Weiss Gallenkamp fitotron (hgc 1514) set at 30 °C and 30% relative humidity ($M_{\theta,<2,30°C}$), and finally, after being dried at 105 °C in an oven ($M_{\theta,<2,od}$). The differences in mass were used to estimate SSA, see Eq. (22) below. The >2 mm material had the organic detritus separated by hand. The organic detritus and remaining >2 mm material were then weighed at field moisture ($M_{\theta,org}$ and $M_{\theta,[2.20]}$ respectively) and after being dried at 105 °C in an oven ($M_{\theta,org,od}$ and $M_{\theta,[2.20],od}$ respectively). The oven-dried >2 mm material was then wet sieved as for the bulk density and >20 mm samples, with clean RFs oven-dried and weighed according to their size classes ($M_{\theta,[2.6],cod}$and $M_{\theta,[6.20],cod}$).

The gravimetric WC (w) of the fine earth ($w_{<2}$) and the fine earth with organic detritus ($w_{<2+org}$) were estimated by,

$$w_{<2} = \frac{M_{\theta,<2} - M_{\theta,<2,od}}{M_{\theta,<2,od}} \tag{7}$$

$$w_{<2+org} = \frac{M_{\theta,<2} + M_{\theta,org} - M_{\theta,<2,od} - M_{\theta,org,od}}{M_{\theta,<2,od} + M_{\theta,org,od}} \tag{8}$$

By assuming these WCs are equal to the WC of the attached fine earth, the WC of the RFs could be back-calculated by accounting for the water derived from the attached fine earth, whether it be mineral or mineral plus organics, in a sample. The gravimetric water content of the 2–20 mm RFs was estimated by,

$$w_{2.20} = \frac{M_b - M_{b,od} - w_{<2+org}\left(M_{b,od} - M_{b,[2.6],cod} - M_{b,[6.20],cod}\right)}{M_{b,[2.6],cod} + M_{b,[6.20],cod}} \tag{9}$$

Because the bulk sample contained fine earth mixed with organic detritus (such as fine roots), $w_{<2+org}$ was used for calculating $w_{2.20}$. Finally, the w of the >20 mm RFs could be derived as,

$$w_{RF,[>20]} = \frac{M_{RF} - M_{RF,od} - w_{<2}\left(M_{RF,od} - M_{RF,[20.60],cod} - M_{RF,[\rangle 60],cod}\right)}{M_{RF,[20.60],cod} + M_{RF,[\rangle 60],cod}} \tag{10}$$

As the fine earth attached to the >20 mm RFs did not contain organic detritus, $w_{<2}$ was the appropriate water content to use.

The depth of water (h, mm) derived from each soil constituent was estimated by,

$$h_{<2} = \frac{R.M_{b,<2}.w_{\theta<2+org} + w_{\theta<2}\left(M_{RF,od} - M_{RF,[20.60],cod} - M_{RF,[\rangle 60],cod}\right)}{\rho_w A} \tag{11}$$

$$h_{[2.20]} = \frac{R\left(M_{b,[2.6],cod.} + M_{b,[6.20],cod}\right).w_{2.20}}{\rho_w A} \tag{12}$$

$$h_{[>20]} = \frac{w_{RF[\rangle 20]}\left(M_{RF,[20.60],cod} + M_{RF,[\rangle 60],cod}\right)}{\rho_w A} \tag{13}$$

where ρ_w is the density of water, which was assumed to be 1 Mg/m^3 and A is the area of the pit (0.3x 0.3 m = 0.09 m^2). By dividing the volume of water by the volume of the soil constituent, volumetric WCs (VWC), θ, could be estimated,

$$\theta_{<2} = \frac{A.h_{<2}}{V_{T<2}} \tag{14}$$

$$\theta_{[2.20]} = \frac{A.h_{[2.20]}}{V_{T[2.20]}} \tag{15}$$

$$\theta_{[>20]} = \frac{A.h_{[>20]}}{V_{T[>20]}} \tag{16}$$

$$\theta_T = \frac{A\left(h_{<2} + h_{[2.20]} + h_{[>20]}\right)}{V_T} \tag{17}$$

The total porosity (ε) could also be estimated by using the fine earth bulk density and the particle density (ρ_p),

$$\varepsilon = 1 - \frac{\rho_{<2}}{\rho_p} \tag{18}$$

where the particle density measurement method is described below.

Using the different dry weights of the fine earth, the apparent SSA was then estimated following the equation of Parfitt et al. (2001),

$$SSA = \frac{2000\left(M_{\theta,<2,30^\circ C} - M_{\theta,<2,od}\right)}{M_{\theta,<2,od}} \tag{19}$$

Finally, the <10 mm sample was sieved to remove the 2–10 mm RFs, then analysed for soil carbon, total nitrogen, particle size distribution, permanent wilting point and phosphate retention (P-retention). Soil carbon and total nitrogen were analysed using the Dumas dry combustion principle according to the methods described by Leco (2003). Particle size distribution was derived from the pipette method following Claydon (1989). The proportions of sand (p_{sand}), silt (p_{silt}), and clay (p_{clay}) in the range 0–1, were used to classify the texture of the fine earth (Milne et al., 1995). As these fractions are part of a ternary simplex, a structural correlation exists (McNeill et al., 2018). For computational convenience, texture proportions were transformed to a Cartesian system as this generally reduces the apparent correlation between texture fractions by removing the structural correlation component. As per the method used by McNeill et al. (2018) and (Cornell, 1981), the texture proportions were transformed to a Cartesian system by generating two auxiliary variables as follows,

$$\omega_1 = 2p_{sand} - p_{silt} - p_{clay} \tag{20}$$

$$\omega_2 = p_{silt} - p_{clay} \tag{21}$$

The water retention of the fine earth at permanent wilting point (15 bar) was measured using small repacked cores within a pressure chamber (Gradwell and Birrell, 1972). Particle density was measured following the method of Gradwell and Birrell (1972). Ground soil was placed in a bottle, covered with water and then placed in a vacuum desiccator. The bottle was brought to a constant temperature before the water level was then raised to a standard mark in the bottle. The weight of the bottle + soil + water and the oven-dried soil was measured before calculating the ratio of weight of soil to weight of water displaced by the soil. Phosphate retention was evaluated by centrifuging a soil sample with a 32 mol/m^3 P solution before measuring the remaining P in solution (Saunders, 1965). The concentration of P left in solution gives a high degree of differentiation between soils of high and low anion retention and was measured using a QuickChem 87,500 flow injection analyser (Lachat Instruments, 1998g).

2.3. Statistical analysis

Before any statistical analyses were performed, the data set was censored according to relative errors in data values. Many of the variables used in the analyses are derived from calculations on primary variables, with inherent uncertainty. Those uncertainties compound and grow in relative magnitude, especially where subtractions and divisions are involved. We quantified the magnitude of errors, both absolute and relative, by applying Gaussian error propagation (refer to Supplementary file). Increments were removed if the relative error for an increment's fine earth VWC, fine earth bulk density or total porosity was >25%. When RF VWC was the response variable, an additional filter was used, which removed increments in which the relative error for 2–20 mm and >20 mm RF VWC was >25%. As the NZSC Order was used as an explanatory variable, increments from soils belonging to rare soil orders (Pallic (2 pits) and Gley (2 pits)) were also excluded.

To determine if a significant difference in WC exists between the 2–20 mm and >20 mm RF fractions, a rank based fixed effect regression was used. The effect of RFs and irrigation treatment on soil properties were analysed using multiple linear regression. To determine effects, regression models were generated that included all possible explanatory variables (Table 1) with treatment or RF volume at the end, so that the effect of these variables could be determined after taking account of all other explanatory variables. If explanatory variables were derived from the response variable then they were not included, for instance, the fine earth bulk density would not be included as an explanatory variable if the whole soil bulk density was the response variable. When all increments were used in the analysis, depth was included as an

Table 1
List of explanatory variables used in multiple linear regression analysis.

Surface age	C:N
NZSC Order	Fine earth bulk density
Season	15 bar WC
FC matric potential	Texture
Particle density	SSA
Organic carbon	ω_1
Total porosity	ω_2
Whole soil bulk density	Treatment
Nitrogen	Volumetric proportion RFs
Phosphate retention	

explanatory variable; however, depth specific relationships were also determined by using data from particular depth increments only. To ensure sampling over two different seasons did not introduce any error in results, 'season' was included as an explanatory variable in the analysis (Table 1) but was found to have no significant effect on the total VWC.

3. Results

3.1. Variation in soil attributes

Brown soils were the dominant soil order encountered (61%) followed by Recent soils (39%). Soil pits were distributed over two geomorphic surfaces: 80% were on Late Pleistocene glacial outwash, 16% were on Holocene alluvial deposits and 4% were on Late Pleistocene to Holocene alluvial deposits. The soil attributes averaged across the measured pits tended to change with depth (Table 2). The fine earth VWC decreased from 40% in the 0–10 cm increment to 16% by the 50–60 cm increment. This decrease in WC with depth was characterised by notable reductions every 20 cm, which may be consistent with major horizon boundaries (e.g. A horizon: 0–20 cm, B horizon: 20–40 cm and C horizon: 40–60 cm). Both carbon and nitrogen decreased considerably with depth in the top three increments (~1% and ~0.1% per 10 cm, respectively), followed by relatively small decreases with depth in the bottom three increments (~0.2% and ~0.02% per 10 cm, respectively). In contrast, P-retention was lowest in the 0–10 cm increment (22%) and increased with depth until it stabilised at ~36% in the bottom three increments (30–60 cm depths). Particle density increased from 2.58 Mg m^{-3} in the 0–10 cm increment to a constant density of 2.68 Mg m^{-3} in the 40–50 cm and 50–60 cm increments. Average fine earth bulk density was lowest in the 0–10 cm and 50–60 cm increments and relatively constant through the 10–50 cm depths. Whole soil bulk density had the lowest average value in the 0–10 cm increment (1.34 Mg m^{-3}) below which it increased to a relatively constant density of ~2.05 Mg m^{-3} in the 30–60 cm depths.

3.2. Particle size and RF distribution

Within and across the sites there was a good representation of different particle sizes, ranging from 5 to 96% sand, 0 to 67% silt, and 1 to 45% clay (Fig. 4). The proportion of RFs to an increment's volume varied from 0% to 83%. In general, the texture of the fine earth became coarser with depth; the fine earth typically exceeded 50% silt in the 0–10 cm increment compared to >70% sand in the 50–60 cm increment. The volume of RFs also increased with depth: RFs typically made up <13% of the total soil volume in the 0–10 cm increment, but >55% for 40–50 cm and 50–60 cm increments (Fig. 4). The volumetric proportions of 2–6 mm and >60 mm RFs were similar in individual increments, respectively increasing from 1 and 2% in the 0–10 cm increment to 8 and 6% in the 50–60 cm increment. The volumetric proportions of 6–20 mm and 20–60 mm RFs were also similar in any one increment, but increased with depth from 3 and 6%, respectively, in the 0–10 cm increment, to 25 and 21%, in the 50–60 cm increment.

3.3. Water content in rock fragments

The average whole-soil volume of water at FC to 60 cm depth was 142 mm. Averaged across all pits classified as stony soils (soils with >35% RFs by volume within 45 cm of the soil surface), RFs in the 0–60 cm increments accounted for ~10% of the retained water, which was equivalent to ~13 mm. The proportion of soil–water retained in RFs increased with depth, exceeding 35% on average in the 50–60 cm increment (Fig. 5). The total WC of an increment decreased with depth from an average of 36 mm in the 0–10 cm increment to 10 mm in the 50–60 cm increment. Rock fragments accounted for <1% of the water in pits with few to no RFs, to >20% in pits where RFs account for >55% of the volume (Appendix A). For every pit and every depth increment, the 2–20 mm RFs retained at least twice as much water as the >20 mm RFs. The mean VWC for the two size fractions in the 0–60 cm increments were 0.07 and 0.03 for the 2–20 mm and >20 mm RFs, respectively. The VWC for the 2–20 mm RFs and the >20 mm RFs were significantly ($P < 0.0001$) different at all depths below 30 cm (Fig. 6). As a result of few degrees of freedom and a non-normal distribution, the difference in VWC of RFs of different size could not be determined for the 0–10 cm and 10–20 cm increments.

Multiple linear regression analysis was used to determine the effects of other variables on the RF VWC (output data can be found in Appendix B). When whole soil profiles were analysed, as the total volume of RFs increased, their VWC decreased. Furthermore, the WC of the 2–20 mm fraction decreased as the coarser part of the fraction (6–20 mm) increased in abundance. Similarly, for the >20 mm fraction, the VWC decreased as the proportion of the >60 mm RFs increased. We also found that the VWC of particular size fractions were affected by RFs outside that size fraction: 1) in the 40–50 cm increment, the VWC of the 2–20 mm fraction increased with the proportion of 20–60 mm RFs; 2) the VWC of the >20 mm fraction increased as the proportion of 2–20 mm RFs increased (on a whole soil profile basis). Due to few degrees of freedom and the large number of explanatory variables used in the regression analysis, statistical tests could not be refined to individual depth increments for the 0–30 cm depths.

3.4. RF effect on fine earth

Using multiple linear regression, we found several interactions between RFs and fine earth properties (output data found in Appendix C). For instance, the whole soil VWC decreased with increasing RF volume, which is consistent with RFs holding less water than fine earth. Total porosity was positively affected by the volume proportion of 2–20 mm RFs when the whole profile was analysed and at the 20–30 cm and 30–40 cm depths. Total porosity was also positively affected by the 20–60 mm RFs in the 20–30 cm increment. Correspondingly, fine earth bulk density was negatively affected by the volume proportion of 2–20 mm RFs when the whole soil profile was considered, while both the 2–20 mm and 20–60 mm RFs had negative effects to fine earth bulk density in the 20–30 cm increment. The fine earth VWC decreased with increasing RF volume at each depth increment and when whole soil profiles were considered. However, the relationship is not consistently detected when analysis is refined to individual depth increments and RF

Table 2
Changes in average soil attributes of measured pits with depth. Values in parentheses are standard error to one significant figure.

Depth cm	Fine earth VWC %	Carbon %	P* %	Nitrogen %	Particle density Mg m^{-3}	Fine earth bulk density Mg m^{-3}	Whole soil bulk density Mg m^{-3}
0–10	40 (0.9)	3.7 (0.2)	22 (1)	0.34 (0.01)	2.58 (0.01)	1.16 (0.02)	1.34 (0.03)
10–20	38 (0.8)	2.7 (0.1)	25 (1)	0.25 (0.01)	2.62 (0.01)	1.35 (0.02)	1.56 (0.03)
20–30	33 (1)	1.8 (0.1)	30 (2)	0.16 (0.01)	2.65 (0.01)	1.31 (0.02)	1.77 (0.05)
30–40	31 (1)	1.4 (0.1)	35 (3)	0.13 (0.01)	2.67 (0.005)	1.36 (0.04)	1.98 (0.05)
40–50	23 (1)	1.2 (0.1)	37 (3)	0.11 (0.01)	2.68 (0.004)	1.29 (0.04)	2.11 (0.04)
50–60	16 (2)	1.1 (0.1)	35 (3)	0.09 (0.01)	2.68 (0.004)	1.12 (0.06)	2.05 (0.05)

* P-retention.

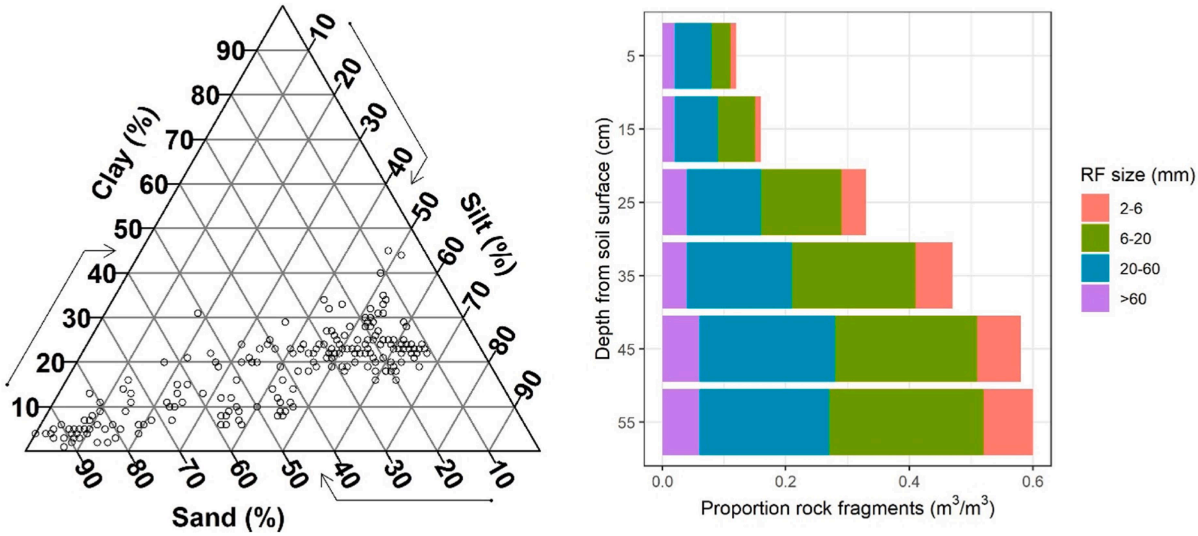

Fig. 4. Left: Soil texture diagram displaying textures for each increment. Right: The proportion of an increment's volume made up of RFs.

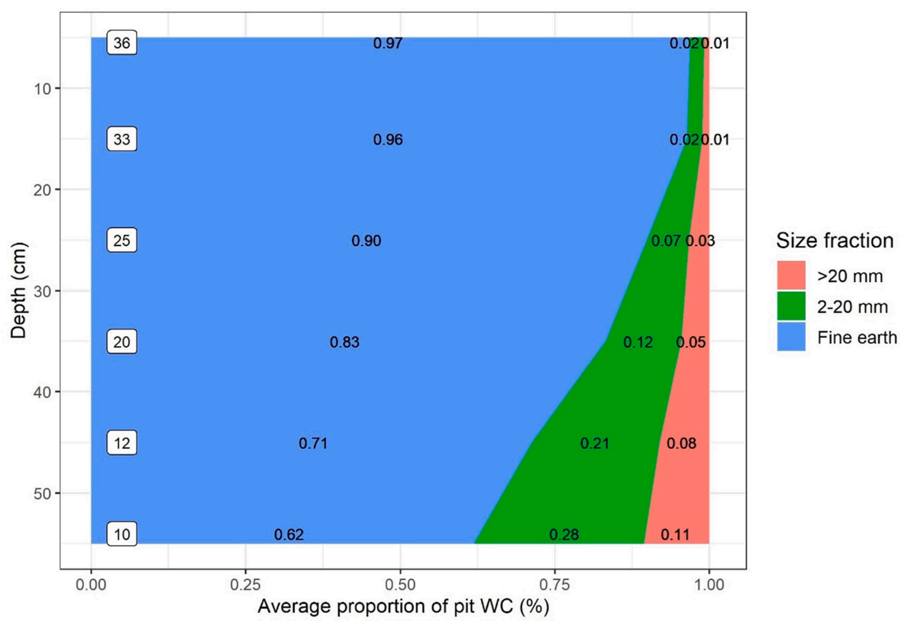

Fig. 5. The average contribution of different size fractions to the total volume of water at different depth increments averaged across all pits. Values in boxes depict the average whole-soil WC in mm for each increment.

size fractions. This is illustrated by the 2–20 mm RFs having a negative effect on fine earth WC when the whole soil profile is considered and at the 30–40 cm depth, whereas the 20–60 mm RFs had a significant negative effect but only when whole soil profiles were considered in the analysis. The >60 mm RFs also had a significant negative effect on fine earth WC, but only in the 0–20 cm increments.

There were also multiple correlations between the volume of RFs and the properties of the fine earth fraction outlined in Table 2 (output data found in Appendix D). Carbon was positively affected by the volume of the 2–20 mm RFs in the 0–10 cm increment but negatively affected by the volume of 6–20 mm RFs in the 40–60 cm increments. P-retention had a positive relationship with the total volume of RFs when whole soil profiles were considered in the analysis. Nitrogen was negatively affected by the volume of 2–6 mm RFs when whole soil profiles were considered and in the 0–10 cm and 20–30 cm increments.

3.5. Treatment effect on fine earth

A history of irrigation had an overall positive effect on the WC of the fine earth when the whole profile was analysed, and when refined to the 10–20 cm increment (regression output data found in Appendix E). No significant relationship was identified between irrigation treatment and total porosity, indicating the effect may be related to the pore size distribution rather than pore concentration. Irrigation treatment had a positive effect on the P-retention in the 10–20 cm increment and a negative effect on soil carbon when the whole profile was analysed.

4. Discussion

4.1. Hard sandstone RFs hold water but not much compared to other lithologies

Our results demonstrate that RFs retain appreciable quantities of

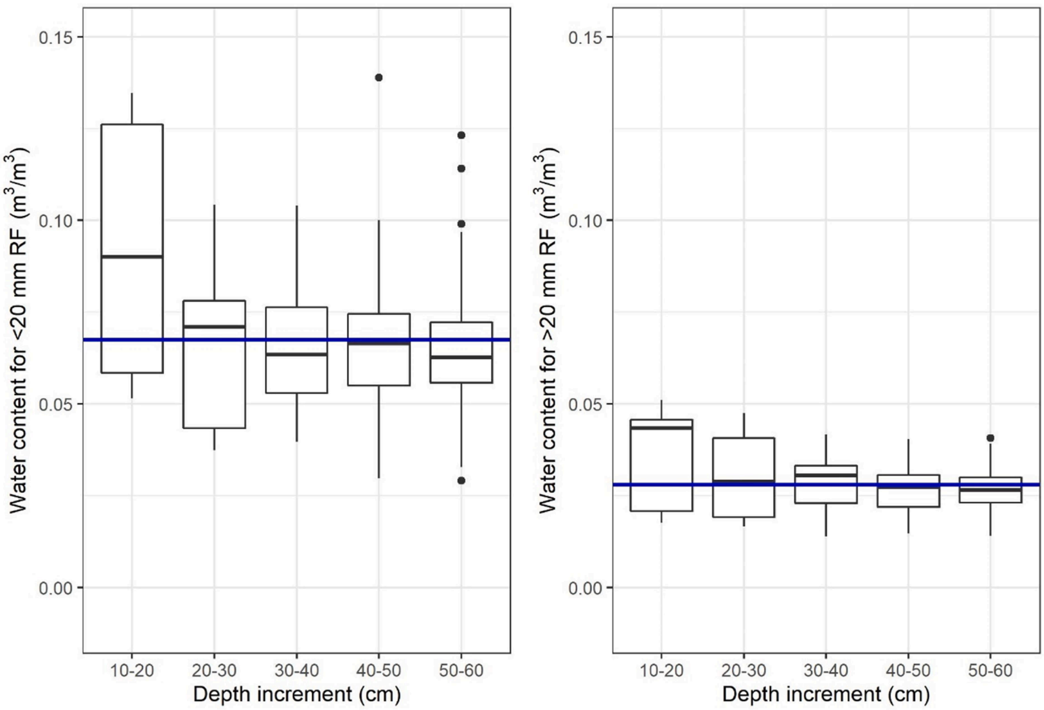

Fig. 6. Comparing the VWC of <20 mm RFs to >20 mm RFs for the 10–60 cm increments. Blue line: Average VWC for the 10–60 cm depths. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water within 60 cm of the soil surface (~13 mm). However, we show that the dominant lithology of RFs on the Canterbury Plains, greywacke – a hard, muddy fine sandstone, holds relatively little water and that the significant contribution they make to water retention arises from their volumetric abundance. Tetegan et al. (2011) found the gravimetric WC of 20–50 mm RFs at FC varied from 0.31 in gaize, 0.21 in chert, and 0.09 in flint, all exceeding the 0.01 (0.03 m^3/m^3) value measured in the >20 mm greywacke sandstone RFs in this study. The generally high bulk density and low porosity for greywacke sandstone (2.51–2.71 Mg/m^3 and 2–4%, respectively), is likely to be responsible (Jones, 2016; McNamara et al., 2014). Other studies of fine sandstone material report average bulk densities of 2.4 Mg/m^3 (Schoeman et al., 1997) and 2.35 Mg/m^3 (Hanson and Blevins, 1979), associated with VWC at FC of >0.07 and >0.14 respectively, both of which are still greater than the 2–20 mm VWC of 0.07 measured in this study. Thus, even amongst fine sandstones, the greywacke sandstone of our study has a higher bulk density and thus lower porosity and water retention.

4.2. *Size and weathering matter*

Our results also show that RF size can affect RF VWC. The significantly higher VWC in the 2–20 mm RF fraction compared to the >20 mm RF fraction we observed is consistent with a number of studies (Poesen and Lavee, 1994; Schoeman et al., 1997), which commonly relate the difference to greater weathering and hence porosity in smaller RFs. Although the thickness of the weathering rind between RF sizes may not vary (as they are exposed to the same weathering conditions), the greater specific surface area of smaller RFs results in a greater proportion of the clast's volume having undergone weathering, resulting in greater water retention. The same finding was also evident within the VWC of the 2–20 mm and >20 mm RFs: the 2–20 mm VWC decreased with an increasing proportion of 6–20 mm RFs; whereas the >20 mm RF VWC was negatively affected by the proportion of >60 mm RFs. The negative effect of the total volume of RFs on the VWC of both the 2–20 mm and >20 mm RFs may also be an expression of how soil age affects the water retention of the RFs. On the Canterbury Plains, older soils have a larger contribution of loess (Ives, 1973), which dilutes the coarse fraction (RFs). Older soils are more likely also to have more weathered RFs, which have higher porosity and store more water (Cuniglio et al., 2009; Tetegan et al., 2011).

Unexpectedly, the 2–20 mm RF VWC was positively affected by the 20–60 mm RFs, whilst the >20 mm RF VWC was positively affected by the 2–20 mm RFs. This may reflect an increase in RF contact points, as some studies have found RFs may store significant quantities of water at contact points between neighbouring RFs or as puddles on the rock surface for larger RFs (Poesen and Lavee, 1994; Schoeman et al., 1997).

4.3. *RF-fine earth interactions*

4.3.1. *Fines VWC*

Besides their ability to retain water, RFs appear to indirectly affect the chemistry, structure and water retention properties of the fine earth. We speculate that the influences of RF abundance on the fine earth VWC are indirect and that the direct causes are changes in matrix grain size that are correlated to RF abundance. For instance, the negative relationship between the total volume of RFs and the fine earth WC is likely due to the strong correlation between RF volume and coarse sand (2–0.6 mm), as coarse sand has low water retention and would negatively affect fine earth WC. The 20–60 mm and >60 mm RFs did not have strong correlations with coarse sand. We expect that these larger RFs may allow water to run freely on the surface of the RFs with little interaction with the adjacent fine earth (Pollacco, 2017; Zhou et al., 2011). We observed this phenomenon where percolating water was diverted around large RFs (>150 mm in diameter) leaving the underlying soil noticeably drier than the surrounding soil. The >20 mm RFs could have a similar effect (albeit not as visible) causing a negative relationship with fine earth WC.

4.3.2. *Porosity and fine earth bulk density*

The decrease in fine earth bulk density and increase in the total porosity with RF volume is consistent with international literature (Baetens et al., 2009; Shi et al., 2012). Poesen and Lavee (1994) attribute RF-induced porosity changes (or changes in fine earth bulk density) to the following:

a. Sedimentary processes can deposit RFs without sufficient fine earth to fill inter RF voids (Lunt and Bridge, 2007), resulting in lower bulk density in the fine earth. Under certain flow regimes, this can ultimately culminate in open framework gravels, a clast-supported coarse layer where little to no fine earth is present (Dann et al., 2009).
b. In a mixture of two particle size grades, the presence of even small numbers of large particles has a negative effect on the bulk density of the smaller particles because the smaller particles cannot pack as closely to the larger particles as they can with each other. Also, fine earth and RFs react in a different way when expanding and contracting (e.g. during the process of wetting and drying or of freezing and thawing), which causes an increase in porosity for the size range>250 μm (Gargiulo et al., 2016).
c. The presence of RFs in the soil changes the nature of the fine earth fraction. With increasing RF content, decaying OM, fertiliser inputs, rainwater etc. are concentrated in a decreasing mass of fine earth, which facilitates the formation of pores and the reduction of fine earth bulk density.

Though the reduction in fine earth bulk density (or increase in total porosity) with increasing RFs is not an uncommon finding, very little of the current literature represents field conditions, with the majority of the research sourced from repacked soil experiments that may be prone to artefacts (da Silva et al., 2016; Gargiulo et al., 2016). Even the studies that measure undisturbed field soils are open to criticism, as they commonly utilise small sample volumes or only sample to a limited depth (Du et al., 2017). Our results not only demonstrate that the RF-fine earth bulk density and RF-total porosity trends occur in the field over a whole region, but that these trends are mostly linked to the 2–20 mm RFs in the 20–40 cm depth increments. The strong correlation with the smaller 2–20 mm RFs is consistent with the results of van Wesemael et al. (1995), who found 17–27 mm RFs negatively affected fine earth bulk density at RF contents of >0.30 Mg Mg^{-1}, compared to the >50 Mg Mg^{-1} RF content required by 77 mm RFs for a similar negative effect to fine earth bulk density to be observed. Between 20 and 40 cm, the soil is generally characterised by a fine-textured matrix (silt loam) with a relatively high RF volume (33–46 m^3 m^{-3} on average for the 20–30 cm and 30–40 cm depths, respectively). We propose that the average clay content in the 20–30 cm and 30–40 cm depth increments (20% and 21%, respectively), imbues sufficient contrast between matrix and RFs in their propensity to shrink and swell on drying and wetting, that lacunar pores develop in the matrix, resulting in a lower fine earth bulk density (Point b. above). When compared to other studies, our in-situ measurements may identify potential issues in using results based on repacked soil experiments. For instance, Fiès et al. (2002) found the volume of lacunar pores increased with the proportion of clasts in the soil but only when clay content exceeded 30%, a value much higher than the 20% observed in this study. Alternatively, Gargiulo et al. (2016) observed an increase in porosity occurring in repacked soils with 18–19% clay content, but only after the soil had been exposed to nine wetting and drying cycles to facilitate the formation of soil structure. These comparisons indicate that for repacked soils to be comparable to undisturbed stony soils, it is necessary for repacked soil to undergo numerous wetting and drying cycles.

4.3.3. Soil chemistry

The significant positive relationship between 2 and 20 mm RFs and carbon in the 0–10 cm increment is reproduced in a number of international studies (Meersmans et al., 2012; Schiedung et al., 2017). This effect is attributed to a concentration of carbon inputs into a smaller volume of fines as the proportion of RFs increases in the topsoil. Alternatively, in the subsoil (40–60 cm depth) the proportion of 6–20 mm RFs had a negative relationship with carbon. This may be due to limitations to plant growth caused by RF proportion (such as reduced water holding capacity or reduced nutrient supply), which could result in reduced carbon inputs at depth if conditions persist for years (Schiedung et al., 2017).

Total nitrogen had a negative relationship with the proportion of 2–6 mm RFs in the 0–10 and 20–30 cm increments while P-retention was positively affected by the volume of RFs when whole soil profiles were considered. We could speculate about the causes of these correlations, but we do not have the data required to support robust inferences.

4.4. Irrigation effects

Irrigation was found to have a significant positive effect on the fine earth WC when the whole profile was analysed and when refined to the 10–20 cm increment, but no clear effect on the RF WC. Other than a positive effect on P-retention in the 10–20 cm increment, and a negative effect on carbon, no other measured soil property was significantly affected by irrigation. Houlbrooke et al. (2008) and Houlbrooke and Laurenson (2013) found irrigation caused a shift in pore size distribution towards greater microporosity because of compaction from grazing on moist irrigated soils. This positive effect on micropores (water storage pores) could explain the increase in fine earth water content at FC observed in this study; however, as pore size distribution was not determined, we can only speculate. Artigao et al. (2002) and Presley et al. (2004) found after 25 and 30 years of spray irrigation respectively, there was evidence of increased mineral weathering in the soil, which may explain the positive effect of irrigation on P-retention. The negative effect of irrigation on carbon is similar to the results in Mudge et al. (2017) who proposed that irrigation may reduce soil carbon by decreasing root biomass, increasing microbial activity (respiration and decomposition) or by increasing the leaching of existing soil carbon.

4.5. Management effect

Results of this study demonstrate that assuming RFs are inert with respect to soil water retention can lead to non-negligible underestimates of soil water storage. On average, ignoring RFs would lead to a ~10% under-estimate of FC in Canterbury stony soils. These soils have low water storage capacity (Carrick et al., 2013a), and are sensitive to irrigation management. Ignoring ~10% of water storage capacity in soils like this could be significant and raises questions about current management and measurement practices worldwide. The fact that international datasets and national environmental models consider RFs that have a greater porosity (and thus water retention) to those measured in this study as inert, demonstrates a potentially significant source of error with numerous undesirable effects. For example, in New Zealand, environmental protection legislation prescribes nutrient leaching limits for the protection of surface waters and shallow groundwater. Nutrient leaching is estimated with a numerical model, which itself is sensitive to the available water content parameter, and hence FC (McNeill et al., 2018). The sensitivity of nutrient leaching simulations to the water holding capacity of RFs needs to be considered. However, although we have confirmed greywacke RFs in stony soils hold a non-trivial amount of water at FC, it remains to be determined how much of that water is plant available. This question must be the focus of future research.

5. Conclusions

Results of this study demonstrate that hard sandstone RFs in Canterbury stony soils are not inert and can in fact retain water and affect the properties of the fine earth. For instance, RFs had positive relationships with carbon, total porosity and P-retention, and negative relationships with the fine earth bulk density, total nitrogen and fine earth WC. In addition, we found irrigation had a negative effect on soil carbon but a positive relationship with fine earth VWC and P-retention. In terms of water retention, even though hard sandstone has relatively low water storage in comparison to other lithologies, the volumetric abundance of RFs in stony soils means RFs still account for a substantial quantity of the water retained at FC. The water retention of the RFs was found to be strongly influenced by size, whereby the VWC of 2–20 mm RFs was found to be twice that of >20 mm RFs. The proportion of RFs may have positive or negative relationships with RF VWC. Our findings could have significant implications for management practices, such as irrigation scheduling, as the effect of RFs (even those with much greater porosity than those measured in this study) are not currently accounted for in most parts of the world. For New Zealand, this means the ~13 mm of water stored in the RFs of Canterbury stony soils is not being included in water budgets or nutrient discharge predictions, leading potentially to apparent breaches of regulations where there are none or unnecessarily strict limits on land management practices. However, we urge caution in factoring RF water holding capacity into decision-making until we determine the proportion of the water stored in RFs of greywacke lithology that is available to plants. This is the focus of our future work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2020.114912.

References

Al-Yahyai, R., Schaffer, B., Davies, F.S., Munoz-Carpena, R., 2006. Characterization of soil-water retention of a very gravelly loam soil varied with determination method. Soil Sci. 171 (2), 85–93. https://doi.org/10.1097/01.ss.0000187372.53896.9d.

Artigao, A., Ortega, J.F., Tarjuelo, J.M., Juan, J.A.d., 2002. The impact of irrigation application upon soil physical degradation in Castilla-La Mancha (Spain). Adv. Geoecol. 35, 83–90.

Baetens, J.M., Verbist, K., Cornelis, W.M., Gabriels, D., Soto, G., 2009. On the influence of coarse fragments on soil water retention. Water Resour. Res. 45 (7) https://doi.org/10.1029/2008WR007402.

Baruck, J., Nestroy, O., Sartori, G., Baize, D., Traidl, R., Vrščaj, B., Bräm, E., Gruber, F.E., Heinrich, K., Geitner, C., 2016. Soil classification and mapping in the Alps: the current state and future challenges. Geoderma 264, 312–331. https://doi.org/10.1016/j.geoderma.2015.08.005.

Batjes, N.H., 2009. Harmonized soil profile data for applications at global and continental scales: updates to the WISE database. Soil Use Manage. 25 (2), 124–127. https://doi.org/10.1111/j.1475-2743.2009.00202.x.

Carrick, S., Fraser, P., Dennis, S., Knight, T., Tabley, F., 2013a. Challenges for leachate monitoring from alluvial sedimentary soils. In: L.D. Currie, C.L. Christensen (Eds.), Accurate and Efficient Use of Nutrients on Farms, Occasional Report No. 26. Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Carrick, S., Palmer, D., Webb, T., Scott, J., Lilburne, L., 2013b. Stony soils are a major challenge for nutrient management under irrigation development. In: L.D. Currie, C. L. Christensen (Eds.), Accurate and Efficient Use of Nutrients on Farms, Occasional Report No. 26. Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Carrick, S., Rogers, G., Cameron, K., Malcolm, B., Payne, J., 2017. Testing large area lysimeter designs to measure leaching under multiple urine patches. New Zealand J. Agric. Res. 60 (2), 205–215. https://doi.org/10.1080/00288233.2017.1291527.

Claydon, J.J., 1989. Determination of particle size in fine grained soils – pipette method. Division of Land and Soil Sciences Technical Record (LH5), DSIR Division of Land & Soil Sciences.

Cornell, J.A., 1981. Experiments with Mixtures. John Wiley and Sons, New York.

Cuniglio, R., Corti, G., Agnelli, A., 2009. Rock fragments evolution and nutrients release in vineyard soils developed on a thinly layered limestone (Tuscany, Italy). Geoderma 148 (3-4), 375–383. https://doi.org/10.1016/j.geoderma.2008.11.005.

da Silva, L.P., van Lier, Q.D., Correa, M.M., de Miranda, J.H., de Oliveira, L.A., 2016. Retention and solute transport properties in disturbed and undisturbed soil samples. Rev. Bras. Ciênc. Solo 40 (0). https://doi.org/10.1590/18069657rbcs20151045.

Dai, Y.J., Wei, S.G., Nan, W., Xin, Q.C., Hua, Y., Zhang, S.P., Liu, S.F., Lu, X.J., Wang, D. G., Yan, F.P., 2019. A review of the global soil property maps for Earth system models. Soil 5 (2), 137–158. https://doi.org/10.5194/soil-5-137-2019.

Dann, R., Close, M., Flintoft, M., Hector, R., Barlow, H., Thomas, S., Francis, G., 2009. Characterization and Estimation of Hydraulic Properties in an Alluvial Gravel Vadose Zone. Vadose Zone Journal 8 (3), 651–663. https://doi.org/10.2136/vzj2008.0174.

Du, Z., Cai, Y., Yan, Y., Wang, X., 2017. Embedded rock fragments affect alpine steppe plant growth, soil carbon and nitrogen in the northern Tibetan Plateau. Plant Soil 420 (1-2), 79–92. https://doi.org/10.1007/s11104-017-3376-9.

Fiès, J.C., Louvigny, N.D.E., Chanzy, A., 2002. The role of stones in soil water retention. Eur. J. Soil Sci. 53 (1), 95–104. https://doi.org/10.1046/j.1365-2389.2002.00431.x.

Forsyth, P.J., Jongens, R., Barrell (Compilers), D.J.A., 2008. Geology of the Christchurch Area. Institute of Geological & Nuclear Sciences 1:250 000 geologial map 16. GNS Science, Lower Hutt, New Zealand.

Gargiulo, L., Mele, G., Terribile, F., 2016. Effect of rock fragments on soil porosity: a laboratory experiment with two physically degraded soils: Role of rock fragments in physically degraded soils. Eur. J. Soil Sci. 67 (5), 597–604. https://doi.org/10.1111/ejss.12370.

Gradwell, M., Birrell, K., 1972. Soil Bureau laboratory methods. C. Methods for physical analysis of soils. New Zealand Soil Bureau Scientific Report 10C.

Graham, S., Srinivasan, M.S., Faulkner, N., Carrick, S., 2018. Soil hydraulic modeling outcomes with four parameterization methods: comparing soil description and inverse estimation approaches. Vadose Zone J. 17 (1), 170002. https://doi.org/10.2136/vzj2017.01.0002.

Hallett, S.H., Sakrabani, R., Keay, C.A., Hannam, J.A., 2017. Developments in land information systems: examples demonstrating land resource management capabilities and options. Soil Use Manage 33 (4), 514–529. https://doi.org/10.1111/sum.12380.

Hanson, C.T., Blevins, R.L., 1979. Soil water in coarse fragments. Soil Sci. Soc. Am. J. 43 (4), 819–820. https://doi.org/10.2136/sssaj1979.03615995004300040044x.

Hedley, C.B., Payton, I.J., Lynn, I.H., Carrick, S.T., Webb, T.H., McNeill, S., 2012. Random sampling of stony and non-stony soils for testing a national soil carbon monitoring system. Soil Res. 50 (1), 18–29. https://doi.org/10.1071/SR11171.

Hewitt, A.E., 2010. New Zealand Soil Classification. Landcare Research Science Series no. 1. 3rd ed. Manaaki Whenua Press, Lincoln, New Zealand.

Hlavacikova, H., Novak, V., Holko, L., 2015. On the role of rock fragments and initial soil water content in the potential subsurface runoff formation. J. Hydrol. Hydromech. 63 (1), 71–81. https://doi.org/10.1515/johh-2015-0002.

Houlbrooke, D.J., Laurenson, S., 2013. Effect of sheep and cattle treading damage on soil microporosity and soil water holding capacity. Agric. Water Manage. 121, 81–84. https://doi.org/10.1016/j.agwat.2013.01.010.

Houlbrooke, D.J., Littlejohn, R.P., Morton, J.D., Paton, R.J., 2008. Effect of irrigation and grazing animals on soil quality measurements in the North Otago Rolling Downlands of New Zealand. Soil Use Manage. 24 (4), 416–423. https://doi.org/10.1111/j.1475-2743.2008.00183.x.

Ives, D., 1973. Nature and distribution of loess in Canterbury, New Zealand. New Zealand J. Geol. Geophys. 16 (3), 587–610. https://doi.org/10.1080/00288306.1973.10431382.

Jones, T.P.C., 2016. Physical and mechanical controls of matrix permeability on rocks from Rotokawa Geothermal Field, Taupo Volcanic Zone, New Zealand, University of Canterbury.

Korboulewsky, N., Tétégan, M., Samouelian, A., Cousin, I., 2020. Plants use water in the pores of rock fragments during drought. Plant Soil 454 (1-2), 35–47. https://doi.org/10.1007/s11104-020-04425-3.

Lachat Instruments, 1998g. Quik Chem Method 12-115-01-1-J, Milwaukee, WI, USA.

Leco, 2003. Total/Organic Carbon and Nitrogen in Soils. Organic Application Note 203-821-165, LECO Corporation, St. Joseph, MO.

Lee, M., 2019. Prescriptions for optimal management of stony soils at Te Whenua Hou in Canterbury. Lincoln University, New Zealand.

Lunt, I.A., Bridge, J.S., 2007. Formation and preservation of open-framework gravel strata in unidirectional flows. Sedimentology 54 (1), 71–87. https://doi.org/10.1111/j.1365-3091.2006.00829.x.

Manaaki Whenua - Landcare Research, 2019. S-map - New Zealand's national digital soil map. 10.7931/L1WC7.

McNamara, D., Faulkner, D., McCarney, E., 2014. Rock properties of greywacke basement hosting geothermal reservoirs, New Zealand: Preliminary results, Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

McNeill, S.J., Lilburne, L.R., Carrick, S., Webb, T.H., Cuthill, T., 2018. Pedotransfer functions for the soil water characteristics of New Zealand soils using S-map information. Geoderma 326, 96–110. https://doi.org/10.1016/j.geoderma.2018.04.011.

Meersmans, J., Martin, M.P., De Ridder, F., Lacarce, E., Wetterlind, J., De Baets, S., Le Bas, C., Louis, B.P., Orton, T.G., Bispo, A., Arrouays, D., 2012. A novel soil organic C model using climate, soil type and management data at the national scale in France. Agron. Sustain. Dev. 32 (4), 873–888. https://doi.org/10.1007/s13593-012-0085-x.

Milne, J., Clayden, B., L., S.P., Wilson, A.D., 1995. Soil Description Handbook. Manaaki Whenua Press, Lincoln, New Zealand.

Mudge, P.L., Kelliher, F.M., Knight, T.L., O'Connell, D., Fraser, S., Schipper, L.A., 2017. Irrigating grazed pasture decreases soil carbon and nitrogen stocks. Glob. Change Biol. 23 (2), 945–954. https://doi.org/10.1111/gcb.13448.

Parajuli, K., Sadeghi, M., Jones, S.B., 2017. A binary mixing model for characterizing stony-soil water retention. Agric. Forest Meteorol. 244-245, 1–8. https://doi.org/10.1016/j.agrformet.2017.05.013.

Pineda, M.C., Viloria, J., Martínez-Casasnovas, J.A., Valera, A., Lobo, D., Timm, L.C., Pires, L.F., Gabriels, D., 2018. Predicting soil water content at − 33 kPa by pedotransfer functions in stoniness 1 soils in northeast Venezuela. Environ. Monit. Assess. 190 (3), 161. https://doi.org/10.1007/s10661-018-6528-3.

Poesen, J., Lavee, H., 1994. Rock fragments in top soils: significance and processes. Catena 23 (1-2), 1–28. https://doi.org/10.1016/0341-8162(94)90050-7.

Pollacco, J., 2017. Literature review of hydrological processes of soils with rock fragments. LC2688, Landcare Research.

Presley, D.R., Ransom, M.D., Kluitenberg, G.J., Finnell, P.R., 2004. Effects of thirty years of irrigation on the genesis and morphology of two semiarid soils in Kansas. Soil Sci. Soc. Am. J. 68 (6), 1916–1926. https://doi.org/10.2136/sssaj2004.1916.

Román Dobarco, M., Bourennane, H., Arrouays, D., Saby, N.P.A., Cousin, I., Martin, M.P., 2019. Uncertainty assessment of GlobalSoilMap soil available water capacity products: a French case study. Geoderma 344, 14–30. https://doi.org/10.1016/j.geoderma.2019.02.036.

Saunders, W.M.H., 1965. Phosphate retention by New Zealand soils and its relationship to free sesquioxides, organic matter, and other soil properties. New Zealand J. Agric. Res. 8 (1), 30–57. https://doi.org/10.1080/00288233.1965.10420021.

Scheinost, A.C., Sinowski, W., Auerswald, K., 1997. Regionalization of soil water retention curves in a highly variable soilscape, I. Developing a new pedotransfer function. Geoderma 78 (3-4), 129–143. https://doi.org/10.1016/S0016-7061(97)00046-3.

Schiedung, H., Tilly, N., Hütt, C., Welp, G., Brüggemann, N., Amelung, W., 2017. Spatial controls of topsoil and subsoil organic carbon turnover under C3–C4 vegetation change. Geoderma 303, 44–51. https://doi.org/10.1016/j.geoderma.2017.05.006.

Schoeman, J.L., Kruger, M.M., Loock, A.H., 1997. Water-holding capacity of rock fragments in rehabilitated opencast mine soils. South African J. Plant Soil 14 (3), 98–102. https://doi.org/10.1080/02571862.1997.10635089.

Shangguan, W., Dai, Y., Duan, Q., Liu, B., Yuan, H., 2014. A global soil data set for earth system modeling. J. Adv. Model. Earth Syst. 6 (1), 249–263. https://doi.org/10.1002/2013MS000293.

Shi, Z.J., Xu, L.H., Wang, Y.H., Yang, X., Jia, Z., Guo, H., Xiong, W., Yu, P., 2012. Effect of rock fragments on macropores and water effluent in a forest soil in the stony mountains of the Loess Plateau. China. Afr. J. Biotechnol. 11 (39), 9350–9361.

Tetegan, M., Nicoullaud, B., Baize, D., Bouthier, A., Cousin, I., 2011. The contribution of rock fragments to the available water content of stony soils: Proposition of new pedotransfer functions. Geoderma 165 (1), 40–49. https://doi.org/10.1016/j.geoderma.2011.07.001.

Twarakavi, N.K.C., Sakai, M., Simunek, J., 2009. An objective analysis of the dynamic nature of field capacity. Water Resour. Res. 45. doi: 10.1029/2009wr007944.

UMS, 2009. User Manual: T5/T5x Pressure Transducer Tensiometer. UMS GmbH München.

van Wesemael, B., Poesen, J., de Figueiredo, T., 1995. Effects of rock fragments on physical degradation of cultivated soils by rainfall. Soil Tillage Res. 33 (3-4), 229–250. https://doi.org/10.1016/0167-1987(94)00439-L.

Webb, T.H., Lilburne, L.R., 2011. Criteria for defining the soil family and soil sibling: The fourth and fifth categories of the New Zealand Soil Classification. Landcare Research Science Series No. 3. Manaaki Whenua Press, Lincoln, New Zealand.

Zhou, B.B., Shao, M.A., Wang, Q.J., Yang, T., 2011. Effects of different rock fragment contents and sizes on solute transport in soil columns. Vadose Zone J. 10 (1), 386–393. https://doi.org/10.2136/vzj2009.0195.